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BINAURAL SUMMATION—A CENTURY OF INVESTIGATION*

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The consideration of binaural hearing in general texts is very often limited to the phenomena of localization and binaural beats. A much neglected aspect of this topic is the ability of the binaural apparatus to summate stimuli that are introduced simultaneously in both ears. This review attempts to summarize experiments of the last hundred years that have revealed evidence for or against such binaural summation. Most of the evidence comes from the comparison or contrast of binaural and monaural sensitivity.

A discussion of the investigations of binaural summation during the past century will be facilitated by dividing the field into two distinct areas. Many observations indicate that a definitely supraliminal auditory stimulus sounds louder when heard with two ears than with only one ear; this phenomenon will be referred to as binaural summation of loudness. Other observations demonstrate that in order to produce a threshold judgment an auditory stimulus does not need to be so intense '„vhen presented binaurally as it does when it is presented monaurally. Binaural summation at threshold refers to these indications that the absolute binaural threshold is lower than the absolute monaural threshold.

Experiments dealing exclusively with binaural summation did not come into the literature until about 1930, Before that time the topic of binaural summation was buried in the experiments on binaural localization and binaural beats. This makes it virtually impracticable to review alt the experiments relevant to binaural summation, but enough of these studies will be reported to give the reader an impression of a continuous trend in the thinking on this subject.

Experiments on binaural localization and beats conducted in the nineteenth century have already been reviewed by Rostosky (27) and

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Melati (23), Both these reviewers, however, smother the issues of binaural summation beneath the then (ca. 1900) more interesting and general topics of beats and localization.

BINAURAL SUMMATION OF LOUDNESS

It was just a century ago that Seebeck (28) in an experiment on the observation of binaural beats, reported that a given amount of sound from his siren seemed louder to two ears than to only one. He mounted two disks with holes punched at equal distances around their peripheries on an axle which was placed behind the observer's head. A stream of air was directed against each of the spinning disks and the sound produced was led from each disk through a tube to each of the ears. For monaural listening one of the air streams was shut off. If the tubes leading from the disks to the ears were equal in length the sounds stimulating the two ears were assumed to be in phase. Seebeck could, however, change the length of one of the tubes so that the sounds stimulating the ears were 180^0 out of phase. He observed that a sound heard binaurally was always louder than the same sound heard monaurally, whether the sounds stimulating the fivo ears were in phase or 180^0 out of phase. If there is a difference between the two binaural cases, said Seebeck, it is certainly difficult to observe.

Although Mach (22) confirmed Seebeck's observation that a tone sounds louder to two ears than to one, he pointed out that the sound heard binaurally seemed louder when the stimuli presented to the two ears were in phase than when they were 180^0 out of phase. In his experiment the sound from a tuning fork was fed to three rubber tubes. Tubes a and b, leading to the left ear, were equal respectively to one and onehalf wave-length. Tube c, leading to the right ear, was equal to one wave-length. The sound fed through tubes a and c seemed louder than the sound fed through tubes b and c (i.e., tones in phase sounded louder than tones out of phase), and both of these combinations sounded louder than the sound fed through all three tubes (actually right ear only since tubes a and b together would cancel the sound for the left ear).

An early attempt to quantify the increase in loudness which is accomplished in binaural listening was made by Docq (7) in 1870. Here we find one of the early considerations of the advantages of an anechoic (without echo) experimental site. Docq carefully described " . . .garden whose horizontal surface was covered with grass which reduced reflected sound by scattering the incident waves" (7, p. 19). The sound source was a

large clock which could be moved back and forth in front of the observer. Docq equated the loudness of the clock-ticks heard

with one ear to the loudness of the clock-ticks heard with two ears by moving the clock back and forth. He found that the ratio of distances for two ears to distances for one ear was about two to one. That is to say, in order to evoke judgments of equal loudness, the clock had to be twice as distant from the observer listening with two ears as it was when he listened with one ear. Further observations with different sound sources such as a music box, violin, and organ pipes resulted in ratios that were greater than two to one. The procedure for listening with one ear was simply to place the finger in the meatus of the opposite ear.

Docq suggested some possible explanations for the decreased loudness in monaural listening or, as he put it, for the fact that the auditory capacity of the two ears functioning together is more than double the capacity of one ear functioning alone. First, he suggested that the presence of a finger in one ear might cause malfunctioning. Second, he felt that the action of a single auditory nerve was incomplete and abnormal and that this abnormality was reflected back to the other ear, making it function less efficiently. Although Docq's observations have been recorded in several secondary sources, his explanations seem never to have been taken very seriously.

In noting analogues to binocular vision, Fechner (8) reported that stopping up one ear with a finger decreases the total loudness, ancl also that greater loudness results if two forks of the same pitch are sounded, one beside each ear, than when one alone is sounded. His notion of the excitations from the two ears combining to give one total impression will be considered later.

In the period of time between these observations of Seebeck, Mach, Fechner, and Docq, and the important second volume of Stumpf's Tonpsychologie (31) of 1890, there appear to be no further considerations of a supraliminal interaural intensification (Verstärhung) although "rwe find in this period observations on the relation of binaural to monaural thresholds, observations which will occupy us presently,

Carl Stumpf had great influence on his students and his conclusions in this matter of binaural summation remained unchallenged for many years. With regard to the greater loudness experienced in binaural listening Stumpf suggested that these early observers had allowed themselves to become victims of an illusion. Of course, said Stumpf, we all know that sounds are fuller, clearer and have greater volume (Tongrösse) when they

are heard with two ears. So, you see, what they really heard as an increase in clarity, fullness, and volume, they thought they heard as an increase in loudness.

There seems to be a great temporal gap, after 1890, in studies on binaural vs. monaural loudness. The next experiment was not until 1929 when Békésy (1) equated in loudness a tone led to one ear with a pair of tones led to two ears. When the two tones heard binaurally were of the same frequency, perfect summation was observed; i.e., the intensity of the single tone was twice the intensity of each of the binaurally presented tones when the observer equated loudness. As the two tones presented binaurally became disparate in frequency the summation decreased. These observations corroborate by analogy some earlier observations by Bloch (2) on binaural summation at threshold.

In 1933, Fletcher and Munson (9) reported data on the difference in the loudness level* at which tones heard monaurally and binaurally sound equally loud. Three frequencies were tested: 125, 1000, and 4000 cps. The difference in loudness level at which the two tones, one heard monaurally and one binaurally, sounded equally loud varied as a function of the loudness level of the tone heard monaurally. A tone in one ear at 108 db loudness level sounds equal in loudness to a tone of 100 db loudness level in two ears. A monaural loudness level of 72 db sounds equal in loudness to a binaural loudness level of 60 db, A monaural loudness level of 25 db sounds equal in loudness to a binaural loudness level of 20 db. If the curve is extrapolated to threshold, we find a difference of 3 db between the monaural and binaural thresholds.

Fletcher and Munson held that the loudness of a tone presented to two ears is just twice the loudness of the same tone presented to only one ear. Churcher (6) argued that this loudness relation of Fletcher and Munson gave support to a nerve-impulse theory of hearing. With twice as many neural impulses set up, the loudness would be twice as great, he said.

Indeed we find certain confirmation of this psycho-neural relation in the experiments of Kemp and Robinson (16). These experimenters observed that the electrical response in either lateral lemniscus at the midbrain level was just twice as great when two ears were stimulated by a tone as when only one ear was stimulated by the same tone. According to these authors, there is little or no interaction between the ears, at least up to the midbrain level. Twice the electrical response and twice the loudness for binaural stimulation suggests a system that has two fairly independent feeders.

More recent data of Caussé and Chavasse (S) are somewhat at variance with the data of Fletcher and Munson. Caussé and Chavasse had their subjects adjust the intensity of a tone presented binaurally until

* The loudness level of a tone is defined as the intensity level of a 1000-cycle tone that sounds equally loud.

it sounded equal in loudness to a tone of fixed intensity presented monaurally. Their results indicate that the difference in intensity increases from 3 db at threshold to a maximum of 6 db at a sensation level of 35 db. From 35 to 60 db the difference remains constant.

To recapitulate, these studies on the difference between the loudness of a sound heard binaurally and the loudness of the sound heard monaurally indicate quasi-unanimity with regard to the existence of some increase in loudness as a result of adding a second ear to the listening system. The sole objector has been Stumpf who insisted that it is not loudness that is being judged when a difference between one and two ears is reported. Precise quantification of the difference between binaural and monaural loudness has not yet been made.

BINAURAL SUMMATION AT THRESHOLD

One of the earliest observations on binaural summation at threshold was made by LeRoux (20) in 1875. He reported to his medical colleagues that the addition of a supraliminal sound to one ear would make a formerly subliminal sound in the opposite ear audible. He demonstrated this effect with two tuning forks, large enough not to attenuate too rapidly. First, he struck one and held it to one ear until the sound decayed just below threshold, Then he struck the other fork and held it up to the opposite ear. The addition of this supraliminal sound in the opposite ear made the first fork again audible

We find an early report on the binaural threshold in a paper written in 1878 to show how the then new Bell telephone could be used to listen to nerve and muscle action currents. Tarchanow (32) wrote as follows: "I had made these observations with one telephone until I learned that our brain contains the capacity to summate tonal stimuli that are impressed on both ears and in this way to bring about louder tonal sensation" (32, p. 354). Although he speaks of "louder tonal sensations," his observations verifying this statement were made at threshold. Tarchanow used a Dubois-Reymond'schen Schlitten-Apparai (which seems to be a precursor of the Wagner and Neef hammers, both of which are prototypes of the electric

doorbell) to induce voltages in an induction coil which was connected to a telephone. He weakened the intensity in one earphone until it was no longer heard. Then he brought the intensity in the opposite earphone up to the same (subliminal) level and noted that the sound was again heard and localized in the middle of the head. "We perceive the tone in consciousness as going out from this median point, and thus it seems more intense" (32, p. 354). In addition to this threshold observation, Tarchanow noted that supraliminal

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sounds heard with two ears sounded louder than the same sounds heard in only one ear. He noted further that the two sounds had to be of the same intensity and frequency in order to summate. In support of this generalization he reported that persons with unilateral hearing loss do not show this summation but rather hear the sound always in their good ear. What he meant by "the same intensity" was the same subjective intensity or loudness. This requirement of equated louclness or equal sensation level for binaural threshold summation has been shown recently to be quite correct (3, 29), but the necessity for the two tones to have the same frequency does not seem to hold. Apparently T archanow was the first to suggest that there must be some kind of central summating mechanism.

We find two direct confirmations of Tarchanow's results in the following year (1879). Preyer (25) and Körting (19), using essentially the same apparatus, confirmed (still without quantification) the observation that a sound which is just too weak to be heard monaurally can be heard binaurally. In addition to reporting his observations, Preyer joined Tarchanow in proposing some kind of summation in the brain.

In 1883, Fechner (26) insisted that the Tarchanow-Preyer proposal of central summation could not be accepted until an experiment could be devised whereby two sound sources would yield a greater sensation when they are separated, one to each ear, than when they are sounded together, both to one ear. This argument will come up again when we discuss Stumpf and von Hornbostel, both of whom repeated it. Further Fechner pointed out that a mixing (Mischung) of auditory nerves in the brain had not yet been shown, even though a binaurally heard tone produces one, not two, perceptions. He suggested that the auditory (…)

duced by both forks, Fechner (26) put forth the same argument in 1883. Stumpf could not see the necessity for proposing some kind of central summation when the evidence was merely the fact that two forks (one to each ear) sounded louder or could be heard with smaller intensity than one (at either ear), He made the observation that Fechner had suggested and used both of the forks in the monaural observation as well as the binaural.

Stumpf argued that the intensity in both cases is the same. If he argued thus he must have assumed that there is a central mechanism which makes the divided intensity look like the same whole intensity; yet he actually uses this argument. to deny t.hat any central mechanism need be invoked.

Three years later (1893) Urbantschitsch (34) took issue with Stumpf on the basis of carefully controlled observations, Urbantschitsch used telephones which were driven by a Neef's hammer and an induction coil. With a meter in the primary coil he could calculate the intensity of the current through the phone. He found that in monaural listening this current had to be approximately twice the amount needed in binaural listening for a just noticeable sensation. A further observation (cf. Tarchanow, 32) was that this ratio of currents held only in the case of persons who had equally acute hearing in both ears. In persons with unilateral hearing loss, Urbantschitsch did not find this summation. On the other hand, if he compensated for the difference in hearing by plugging the better ear, then indeed the summation was observed. (This was what Shav,/, Newman and Hirsh believed in 1947 W'as their "novel" technique.) Another important qualification, according to Urbantschitsch, was that the two tones should have the same pitch. This requirement has not been confirmed.

In the same year, Bloch (2) confirmed the observations of Urbantschitsch and agreed with him that a central summation must take place. He disagreed, however, with Urbantschitsch's requirement that the tones led to both ears must bc of the same pitch. Bloch showed that when the two tones were of the same frequency the ratio of currents for monaural and binaural thresholds was maximum. The magnitude of the ratio decreased as the interval between the frequencies of the two tones increased (cf. Békésy, 1).

The next two decades secrn to contain no new investigations of either binaural summation of loudness or binaural summation at threshold. Both Rostosky (27) and Melati (23) published excellent historical reviews in their papers on binaural hearing. We find their reports on binaural summation, however, couchccl in a context of binaural beats and not suitably drawn together for present purposes.

In 1919, another argument was brought to bear on the Stumpfian view that binaural summation is no more than the normal, mechanical summation. Klemm (18), using electro-magnetically driven tuning forks, measured the current necessary to drive the forks for both monaural and binaural thresholds. His measures show a ratio that is clearly larger than the ratios of Urbantschitsch (34) and Bloch (2). The ratio of the tuning fork amplitudes for monaural and binaural thresholds was four to one. Since

mechanical summation would predict only a two-toone ratio, Klemm argued, there must be some kind of sensory interaction. "Sensory interaction consists in the enhancement of the excitability of one ear by excitation of the other, especially for sounds near threshold" (Klemm, 18, p. 75).

In 1923, von Hornbostel (35) lined himself up on the Stumpfian side of the argument of the physical vs. the more-than-physical summation. He used a single fork which introduced the sound into a rubber tube. The tube was bifurcated, one branch going to one ear and the other branch to the other ear. He observed that when the sound of the fork decayed enough not to be heard in one ear, it again became audible if the second t.ube was brought up to the opposite ear. Von Hornbostel (35) observed further that if both tubes were brought to the same ear the sound was also audible, and that therefore the summation was no more than physical* On the use of underwater direction-finding apparatus he wrote, [i] 'I have often compared monaural with binaural thresholds and have never found a difference" (35, p. 85).

Wittman (36) made observations on a large number of normal and hard-of-hearing people. These studies primarily concerned auditory localization but we find the following remark on binaural summation : . . . the intensity of a binaurally heard sound impression is greater than the monaural impression. If two binaural stimuli are near or under the threshold for monaural hearing, together they will give a distinct sound perception, whereas the monaural would either be perceived weakly or not at all (36, p. 90).

The paucity of material between the 1890's and 1920's is evident in the chapter by Gildemeister (11) in Bethe's Handbuch. His chapter on the thresholds and limits of hearing contains a small section on binaural hearing. There he referred to Stumpf (31) and to von Hornbostel (35) as not being able to confirm the earlier observations on binaural surnmation at threshold. But he also referred to Wittman (36) who sits on the other side of the fence. Gildemeister did not take sides.

The report of Gage (10) in 1932 is apparently the first that is concerned entirely with binaural summation at threshold, It is also the first experiment on the binaural threshold to enjoy the use of vacuum tubes. Gage applied the output of a beat-frequency oscillator to a loudspeaker which was mounted in a heavily damped box. A rubber tube was led out of the box to an acoustic filter and was then bifurcated, Each branch could be shut off by a clamp. In this way Gage could control the intensity in one or both branches and could compare the binaural with the monaural thresholds, Averaging the results of observations on 22 frequencies between 120 and 800 cps, he stated that the binaural threshold was 1.0 db lower than the

better (lower) monaural threshold, and 5.6 db lower than the worse (higher) monaural threshold.

In the following year Sivian and White (30) reported their measurements on minimum audible fields (M.A.F.). These experimenters measured the minimum field required for threshold judgments from observers seated in an anechoic chamber. Sound was introduced to the chamber by a loudspeaker which was suspended one meter away from the 0b, server. Monaural measurements were made on 14 ears and binaural measurements on 12 ears. Different subjects were used in these different sets of measurements and directly comparable data on monaural and binaural thresholds are available for only two subjects. "For two members of the group data were available binaurally as well as on each ear separately. These data show no significant difference between the binaural M.A.F. and the best ear M.A.F. Accordingly, for the three others in the group the best ear M.A.F. was taken to be the binaural M.A.F." (30, p. 295). Sivian and White concluded generally that there is no binaural summation. One might just as well call the binaural threshold the threshold of the better ear, they said. The complications in their treatment and acquisition of data in a free field make it extremely difficult to weigh their decision,

A valuable contribution to binaural summation at threshold was an experiment by Hughes (14) in which the effect of a subliminal monaural stimulus on the contralateral monaural threshold was studied, Actually these were binaural threshold measurements. First Hughes found the monaural thresholds for right and left ears. Then, with sounds that were 3, 4, and 5 db below monaural threshold in the left ear, he remeasured the right threshold. The right thresholds were then found to be 3.1, 2.7, and 2.1 db respectively below their original "unaided" thresholds. Hughes argued that since an ideal summating mechanism would satisfy the following condition :

$$(E_1/E_0)_L + (E_1/E_0)_R = 1$$

where Eo is energy required at threshold and El is some lesser energy, and since the corresponding values from the above observations turn

out to be .99, .94, and .94 respectively, the ear seems to be a good approximation to a perfect summating device.

It is interesting to note that Hughes obtained results of the same order of magnitude with frequencies that were quite different in the two ears, a fact which Urbantschitsch (34) denied, and which contradicted Bloch (2) who had said that the summation decreased as the frequency interval between the sounds in the two ears increased. In a 1940 article, Hughes (15) compared the summation in the ears with physical summation that obtained externally (as Fechner, Stumpf and von Hornbostel had suggested). He led the sound from the two earphones which he had used on both ears to a small, well damped box, In the cases where the two frequencies were different, there was slightly less summation for this monaural threshold than there had been when each of tw'o tones had been led to one or the other ear. The only case in which he found perfect summation in the box was that in which the two sounds were of the same frequency.

In the satne paper, Hughes attempted to measure the effect of contralateral and ipsilateral supraliminal stimuli on the monaural threshold. He found that contralateral audible stimuli have little effect at least up to 15 db sensation level. The monaural threshold is raised, however, when the contralateral stimulus is of the same frequency. These observations were actually observations on localization, for "threshold" turned out to be "level for central localization."

As long ago as 1893, Urbantschitsch (34) had shown that binaural summation could not be demonstrated in unilaterally hard-of-hearing persons unless the better ear was plugged and the two ears thus "equated" in sensitivity. Actually, the difference between the two monaural thresholds of so-called normal observers may be appreciable. In 1947, Shaw, Newman, and Hirsh (29) argued that the difference between monaural and binaural thresholds varied as the sensitivities of the two ears were different. Hughes (14) had already shown what course this difference would take as the ears were mismatched.

An "equating procedure" for normal observers was used by Caussé the difference between the binaural and the equated monaural threshold. This unanimity is shown in Fig. I, where the difference between the binaural and the equated monaural absolute thresholds is plotted as a function of frequency. Shaw, Newman and Hirsh (29) and Keys (17) have reported that the difference between the binaural and equated monaural thresholds of intelligibility for speech is also approximately 3 db.

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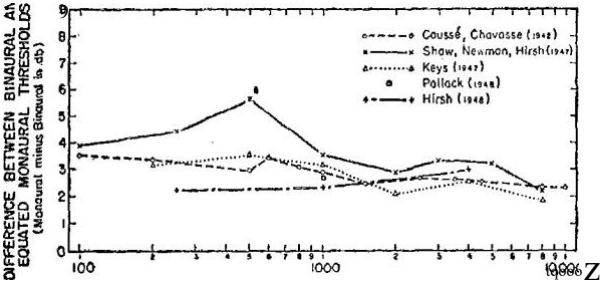

FIG. I. BINAURAL SUMMATION AT THRESHOLD

So far, the review of experiments on binaural summation at threshold has concerned absolute thresholds—thresholds for stimuli presented against a quiet background. More recent work of Hirsh (12, 13) has been concerned with the difference between binaural and monaural masked thresholds—thresholds for stimuli presented against a background of noise. Hirsh has shown that the phase angle between the two earphones for both the noise and the tone is a critical parameter. His results indicate that when the phase angle between the earphones is either 0^0 or 180^0 for both the tone and the noise the binaural threshold is higher than the monaural: some sort of "interaural inhibition" is observed. This interaural inhibition is most marked in the lower range of frequencies between 200 and 500 cps and the effect increases as the noise is made more intense. When the phase angle for the tone is opposite to that for the noise, interaural (or binaural) summation obtains. This interaural summation is most marked in the same range of frequencies as •that in which the interaural inhibition is most marked, and the interaural summation also increases as the noise is made more intense. A corroboration of these results is to be found in the recent work of Licklider (21) on the intelligibility of speech masked by noise, *

* These results of Hirsh and Licklider had been anticipated by observations of Langmuir, Schaefer, Ferguson, and Henelly in '{A Study of the Binaural Perception of the Direction of a Sound Source," NDRC Report 6.1-1840 (June 1944) PB 31014.

SUMMARY

That a supraliminal auditory stimulus sounds louder to two ears than to only one has been known since Seebeck macle his observations a little over a century ago. Stumpf argued that loudness is not the attribute that increases when the second ear is added to the listening apparatus. Seebeck did not observe any change in binaural loudness when the phase angle between the two ears was changed, but Mach did,

Traditionally, binaural summation has referred to the difference between the binaural and monaural absolute thresholds. It has been suggested recently

that this difference depends upon the relative sensitivity of the two ears and that this factor might account for a good part of the disparity among results in the past. Tarchanow, Urbantschitsch, and Bloch recognized that binaural summation could not be shown if the sensitivities of the two ears were markedly different and Urbantschitsch added the restriction that the tones stimulating the two ears must be of the same frequency. Bloch and, more recently, Hughes have shown that this second restriction does not hold.

When the ears of a normal observer are "equated" in sensitivity before binaural listening, the difference between the binaural and the equated monaural thresholds seems to be about 3 db. The variation of this difference as a function of frequency remains to be worked out more precisely.

The simple summative results which obtain when thresholds are measured in the quiet do not apply to thresholds of stimuli which are masked by noise. For certain interaural phase relations between the tone and the masking noise, interaural inhibition may be observed: the binaural threshold is higher than the monaural threshold. For other phase relations, interaural summation (as discussed above) is observed. The adjective interaural has recently been introduced to modify both "summation" and "inhibition." Interaural suggests an interaction betwcen the ears rather than the independent action of two separate ears suggested by binaural.

The experiments which have been reported reveal a considerable amount of evidence on the interaction of the two cars of the human organism, We know that a sound is heard more easily ancl, once heard, sounds louder when an observer uses two cars than when he uses only one. More than that, we know that the clifference in loudness between a tone heard monaurally and a tone heard binaurally varies with intensity. The difference between the binaural and monaural thresholds varies as a function of the frequency of the tonal stimulus and as a function of the level of a background noise against which stimuli are presented.

Explanations which have been deduced by analogy to mechanical or electrical systems have seemed inadequate in the light of subsequent data. It may be hoped that future experimentation will bring to light the parameters which determine interaural summation at threshold and interaural summation of loudness. Only then will we recognize the physiological bases of the phenomena which have been reviewed here and which are yet to be observed.

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